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LM AND CSM S-BAND ANTENNA TRACKING STUDIES
TASK E-53C
ENGINEERING REPORT

TESTING THE CSM S-BAND HIGH GAIN ANTENNA SERVO

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13 DECEMBER 1968

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Under

Contract No. NAS 9-8166

TRW
SYSTEMS GROUP

NASA CR 92495

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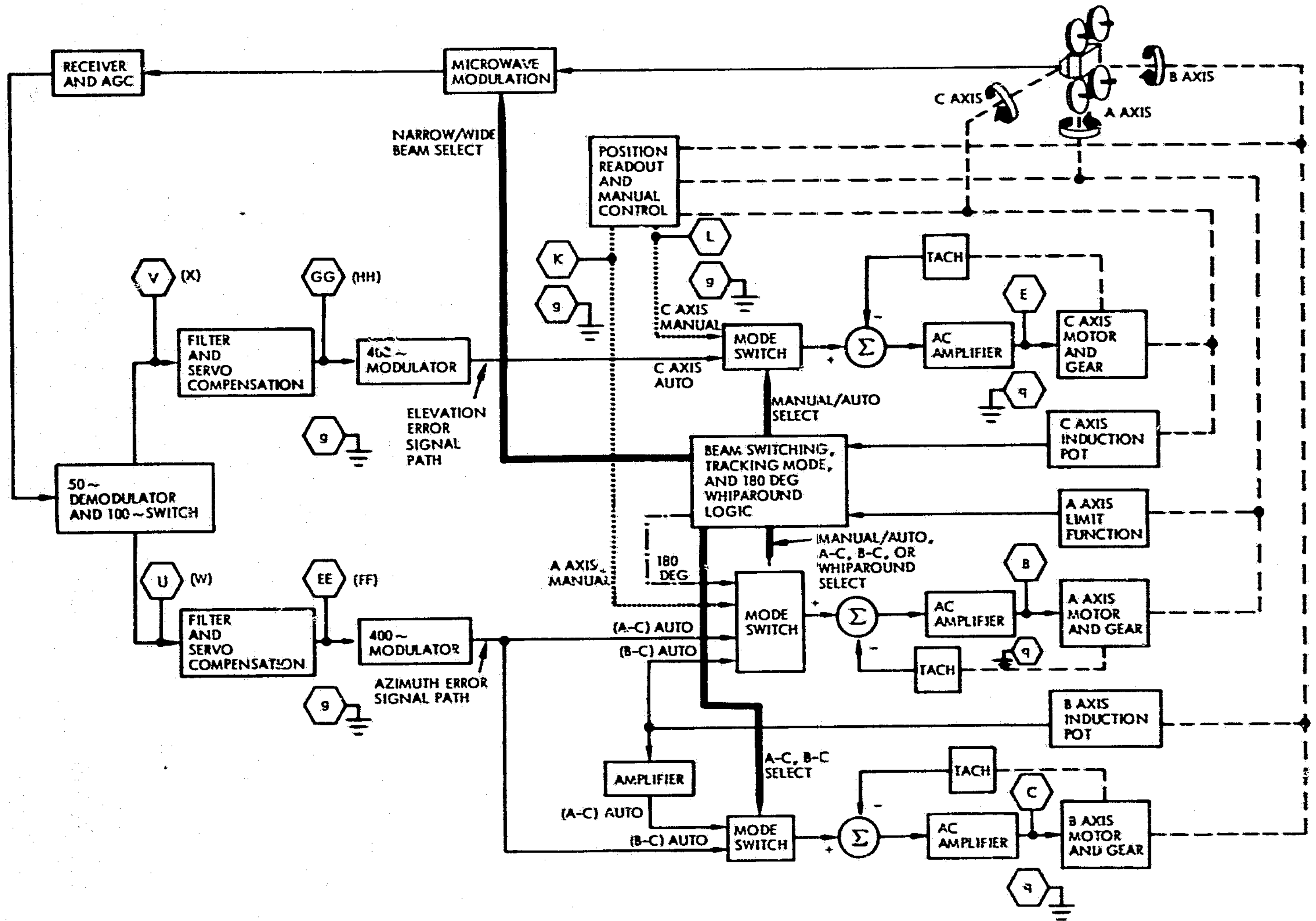
1.0 INTRODUCTION

This report provides techniques for measuring the Command Service Module High Gain Antenna (CSM HGA) servo closed-loop response and the transfer function of the elevation and azimuth compensation network. Test results obtained by the techniques outlined in this report are to be used to verify the analytic model and proper operations of the CSM HGA servo.

The report begins with a brief description of the CSM HGA servo under closed-loop operation. The objectives and methods of the antenna tests are presented in Section 2. They include the type of measurements required, the equipment required, the antenna servo test setup, and the measurement steps for antenna closed-loop and servo compensation response tests.

In addition to the objectives and methods of antenna tests, a section containing the mathematical model of the servo closed-loop and compensation networks transfer characteristics is presented.

This report is supplemented by two appendices which describe the development of the test setup error modulation circuit and the derivation of the error ratio defining the closed-loop response. The functional block diagram of the CSM HGA tracking system is shown in Figure 1. The tracking system is divided into four major sub-assemblies; the Antenna Assembly, S-Band Transponder, Electronics Assembly, and Manual Control Assembly (See Figures 2 & 3). The Antenna Assembly consists of an antenna array, a microwave network, and motors, tachometers, gear trains, induction potentiometers, function generators, and resolvers for the A, B, and C axes. The S-Band Transponder contains a receiver and an AGC circuit which provides the antenna tracking error signals to the Electronics Assembly. The Electronics Assembly



LEGEND:

- AUTO TRACKING SIGNALS
- MANUAL SIGNALS
- WHIPAROUND SIGNAL
- CONTROL SIGNALS
- MECHANICAL CONNECTIONS

FUNCTIONS FOUND ON GROUND SUPPORT EQUIPMENT (GSE):

CONNECTOR AND PIN NO.	FUNCTIONS
J8-EE(FF)	PRIMARY (SECONDARY) A-B - AXIS SERVO COMPENSATION OUTPUT (AZIMUTH ERROR)
J8-GG(HH)	PRIMARY (SECONDARY) C-AXIS SERVO COMPENSATION OUTPUT (ELEVATION ERROR)
J8-K	A-AXIS (AZIMUTH) MANUAL ERROR
J8-L	C-AXIS (ELEVATION) MANUAL ERROR
J8-U(W)	PRIMARY (SECONDARY) A-B - AXIS AUTO ERROR SIGNAL (AZIMUTH ERROR)
J8-V(X)	PRIMARY (SECONDARY) C-AXIS AUTO ERROR SIGNAL (ELEVATION ERROR)
J8-B	A-AXIS MOTOR DRIVE I
J8-C	B-AXIS MOTOR DRIVE I
J8-E	C-AXIS MOTOR DRIVE I
J8-q	DRIVE COMMON
J8-g	DC. COMMON

Figure 1. Functional Diagram of CSM Antenna Tracking System

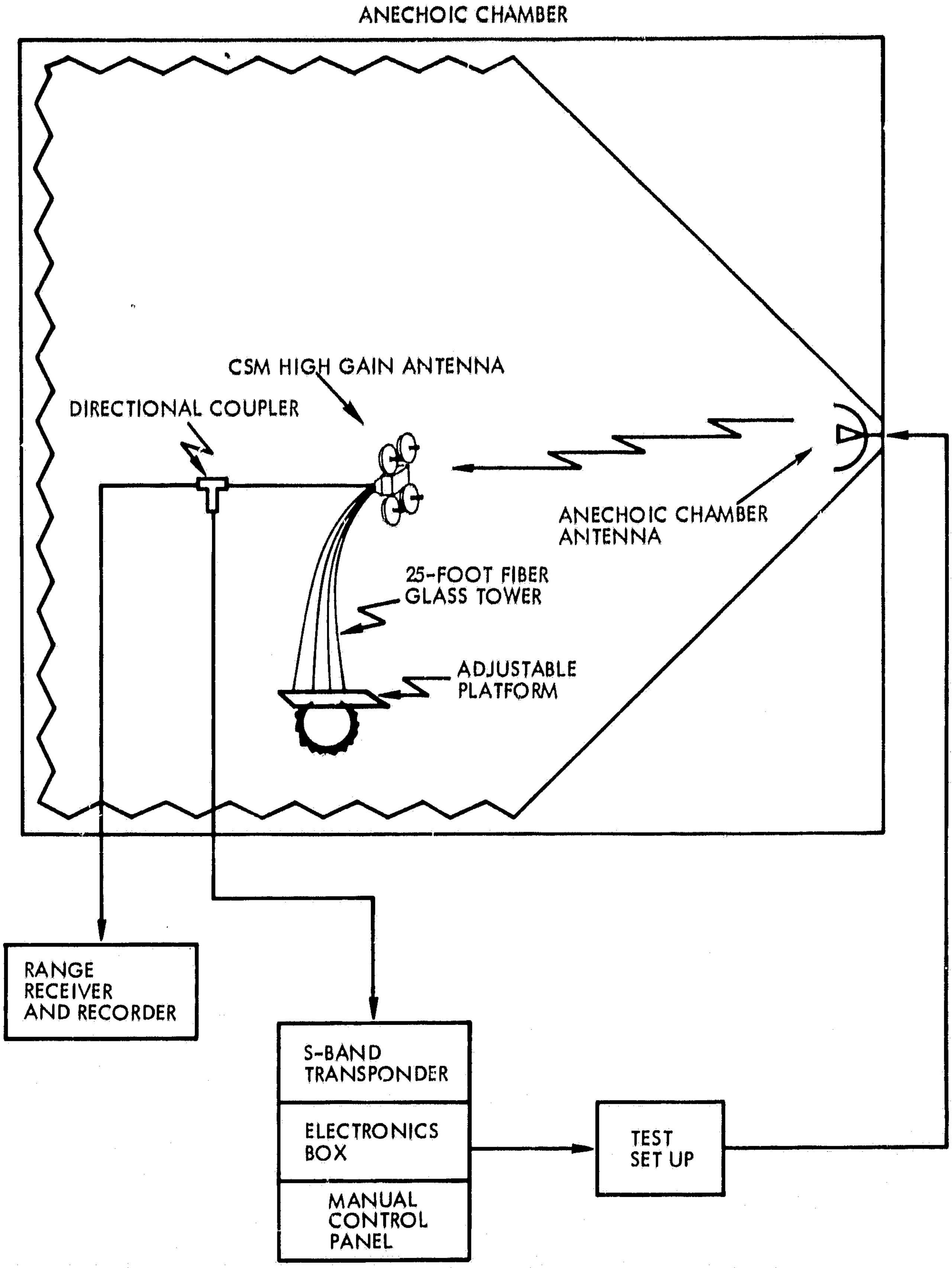


Figure 2. Functional Diagram of Antenna Test

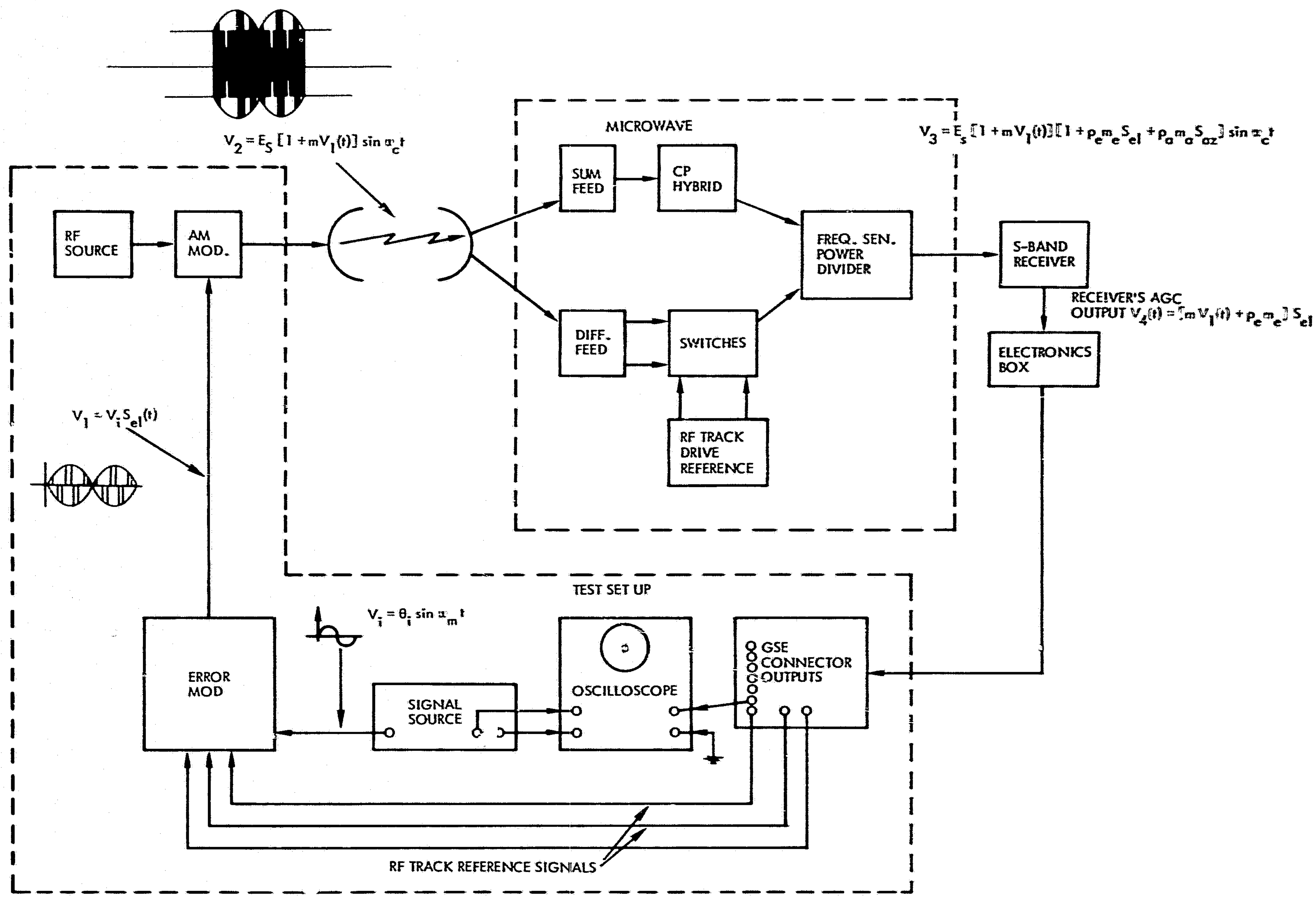


Figure 3. Functional Diagram for Antenna Closed-Loop Test

contains a demodulator, filter and servo compensation networks, modulators, mode switches, amplifiers, and switching logic networks. The Manual Control Assembly consists of resolvers and displays associated with manually positioning the antenna.

The basic test configuration used in previous tests (See Reference 3) conducted at MSC/SESD on the CSM HGA is modified for the tests outlined in this report. As shown in Figure 2, the modifications consist of using an "in house" RF source, measuring the RF received signal from the coupled output of a directional coupler that is inserted into the RF line between the CSM HGA and S-Band Transponder*, and using a test setup that is also shown in Figure 3. A special non-standard piece of equipment required in the test setup is an error modulator described in detail in Appendix A.

Figure 3 shows the functional operation of the antenna closed-loop test. The operation begins from the signal source, continues in a counter-clock-wise direction, and ends at the GSE connector outputs. A low frequency sinusoidal signal from the signal source (V_i) is modulated with a 50 Hz digital sampling signal (S_{e1}), producing a sampled sinusoidal signal (V_1) which is amplitude modulated (AM) by an RF source. The AM modulated signal (V_2) is then transmitted to and received by the CSM HGA. Tracking errors are sensed by sequentially tilting a portion of the antenna beam in two orthogonal directions: up and down in elevation and right and left in azimuth. If the energies received by the tilted beams are equal, there is no pointing error; if the energies received by the tilted beams are not equal, there is a pointing error. The microwave structures within the antenna assembly form the difference between the up and down elevation

*The directional coupler may not be necessary since a Digital Readout of the received S-Band carrier level is available.

received energies and between the right and left azimuth energies, where these azimuth and elevation differences are a measurement of the antenna pointing error. The microwave network sequentially adds these azimuth and elevation error signals to the received carrier signal in the form of amplitude modulation.

The time-multiplexed azimuth and elevation error modulations (V_3) are processed in the S-Band receiver, which produces an AGC voltage (V_4) proportional to the percent (%) AM on the received carrier signal.

The receiver's AGC output signal is processed by a 50 Hz demodulator in the Electronics Assembly (Figure 1), which separates the multiplexed azimuth and elevation signals into separate channels. Following the 50 Hz demodulator are two separate servo compensation networks. The input (V & U) and output (GG & EE) of the servo compensation networks are two of the outputs that are measured in the antenna closed-loop test. The other measured output is the signal source (V_i, Figure 3). The calculated closed-loop response curves are presented in Section 3. A more detailed operational description and analytic model of the CSM HGA may be found in References 1 and 2.

2.0 OBJECTIVES AND METHODS OF ANTENNA TEST

2.1 Types of Measurements

As a result of the limitations of the available test points in the CSM antenna tracking system, two fundamental measurements are outlined in this report to test the CSM HGA servo. The first measurement is the closed-loop response of the CSM HGA antenna servo tracking system. The second measurement is the transfer functions of the servo compensation networks. These measurements may be taken simultaneously. The measurements can then be compared to the closed-loop response curve and servo compensation response curves given in this report, which are determined from an analytical (linear) model of the CSM HGA antenna servo system. The development of the analytic model will be given in a later report concerning the dynamic tracking study.

2.2 Equipment Required for Antenna Test

Basically the same equipment is required that was used in previous HGA tests. The additional equipment is shown in Figures 2 and 3 and listed in Table I*.

The only non-standard piece of equipment used for the tests in this report is the error modulator. The error modulator consist of "off-the-shelf" integrated circuit logic elements, switching transistors, silicon diodes, operational amplifiers, and a double pole, double throw switch. The necessary parts for constructing the error modulator are available at TRW Systems Houston Operations. Essentially the function of the error modulator is to sample a low frequency sinusoidal test signal at the same sampling rates as the error signals in the CSM antenna tracker. In fact, the CSM HGA tracker reference drive signals are used to drive the error modulator switches, thus establishing the necessary synchronous sampling.

2.3 Antenna Servo Test Setup

The functional block diagram of the CSM HGA is shown in Figure 1. Located on the diagram are hexagon call outs which represent the test points that are needed for the measurements described in this report. Identification of these convenient test points were determined by a conversation between MSC/SESD, Dalmo Victor, and TRW Systems and verified in Reference 4, which is a preliminary circuit diagram of the CSM HGA servo electronics. The test points from the servo electronics are conveniently

*The equipment list used in previous tests is given in Reference 1

TABLE I ADDITIONAL EQUIPMENT LIST

Equipment	Comments
Error Modulator	See Appendix A
Signal Source	HP202A or 203A*
Oscilloscope	Tektronix 54AA
RF Source & Amplitude Modulator	HP-8614A*
DC Voltmeter	Standard (Calibrated in decibels)
Equipment for Measuring AM	See Reference 5

*Hewlett Packard Equipment

brought out from the ground support equipment via connector J8. The pins of the cable are identified in Figure 1.

Figure 2 shows the overall test configuration of the CSM HGA tracking system. The test set-up shown in Figure 2 is identified in Figure 3 and the details of the error modulator are given in Appendix A.

To accomplish the tests described in this report, the test facilities at MSC/SESD, Building 14, will be used. The CSM HGA and associated control equipment as shown in Figure 2, is positioned in the center of the Anechoic Chamber of Building 14 and the HGA is connected to a Block II S-Band transponder. Closed-loop operation is conducted with the uplink signal furnished by an S-Band RF source located outside the Anechoic Chamber in the RF Antenna Laboratory.

2.4 Measurement Steps for Antenna Closed-Loop and Servo Compensation Response Tests

The steps to determine the antenna closed-loop response and the servo compensation response are given in this section. They are:

Step 1 - Connect a Directional Coupler (S-Band) into the RF line between the CSM HGA and the Block II S-Band Transponder and to the coupled output of the Directional Coupler, connect the range receiver and recording equipment.

Step 2 - Transmit an S-Band unmodulated carrier from the Anechoic Chamber horn antenna to the CSM HGA. Adjust the transmit power so that the S-Band receiver power is on the order of - 78dBm. Put the HGA in the automatic tracking mode and allow the HGA to move to a stable tracking configuration with the beamwidth switch in the narrow beam position.

Step 3 - Amplitude modulate* the RF carrier with a low frequency (0.01 to 10.0 Hz) sine wave that is sampled with the RF antenna track drive reference signals. Adjust the percent amplitude modulation (%AM) to TBD %** and the amplitude of the low frequency sine wave to TBD volts.** (See Figures 2 and 3).

Step 4- (Read Step 5 before taking measurements). Record and tabulate the output levels (volts and dB) of the servo demodulators (pins J8-U and J8-V), servo compensation networks (pins J8-EE and J8-GG), and the input signal to the amplitude modulator for various input signal frequencies (.01 to 10 Hz). Also record and tabulate the relative phases between the output levels of the servo demodulators, servo compensation networks, and the input AM signal for the same input frequencies mentioned above. These measurements are taken simultaneously.

Step 5 - To insure that saturation has not occured, reduce the input signal level on the % AM transmitted and take a few "spot" measurements as outlined in Step 4. If the phase and amplitude measured in Steps 4 varies, the system was operating in saturation. Reduce the input signal level or % AM and repeat Step 4. It is advisable to go to step 5 while taking measurements

*The method of AM measurements is found in Reference 5.

**TBD-(To Be Determined). The % Am and voltage level are known approximately: Adjustments must be made when actual tests are conducted.

under step 4 so that it is known whether the system was in saturation or not.

Step 6 - Plot on semi-log paper the amplitude ratio (dB) and relative phase versus frequency, where frequency is the abscissa, for the ratio of demodulator output to the AM input and their relative phases and the ratio of servo compensation output to the AM input and their relative phases. Also plot the ratio (dB) of output to input of the servo compensation networks and their relative phases versus frequency. Note that the output of the demodulator is the input to the servo compensation networks.

Step 7 - Compare the curves prepared in step 6 to the curves given in the next section of this report.

3.0 ANALYTICAL MODEL OF THE CSM HGA SERVO

The responses curves obtained from Step 6 of Section 2.4 represents the closed-loop response of the simplified linear servo system shown in Figure 4. The expression for the error ratios are given as:

$$\frac{E(S)}{I(S)} = \frac{1}{1 + G_{OL}(S)} \qquad (1)$$

$$\frac{E'(S)}{I(S)} = \frac{G_C(S)}{1 + G_{OL}(S)} \qquad (2)$$

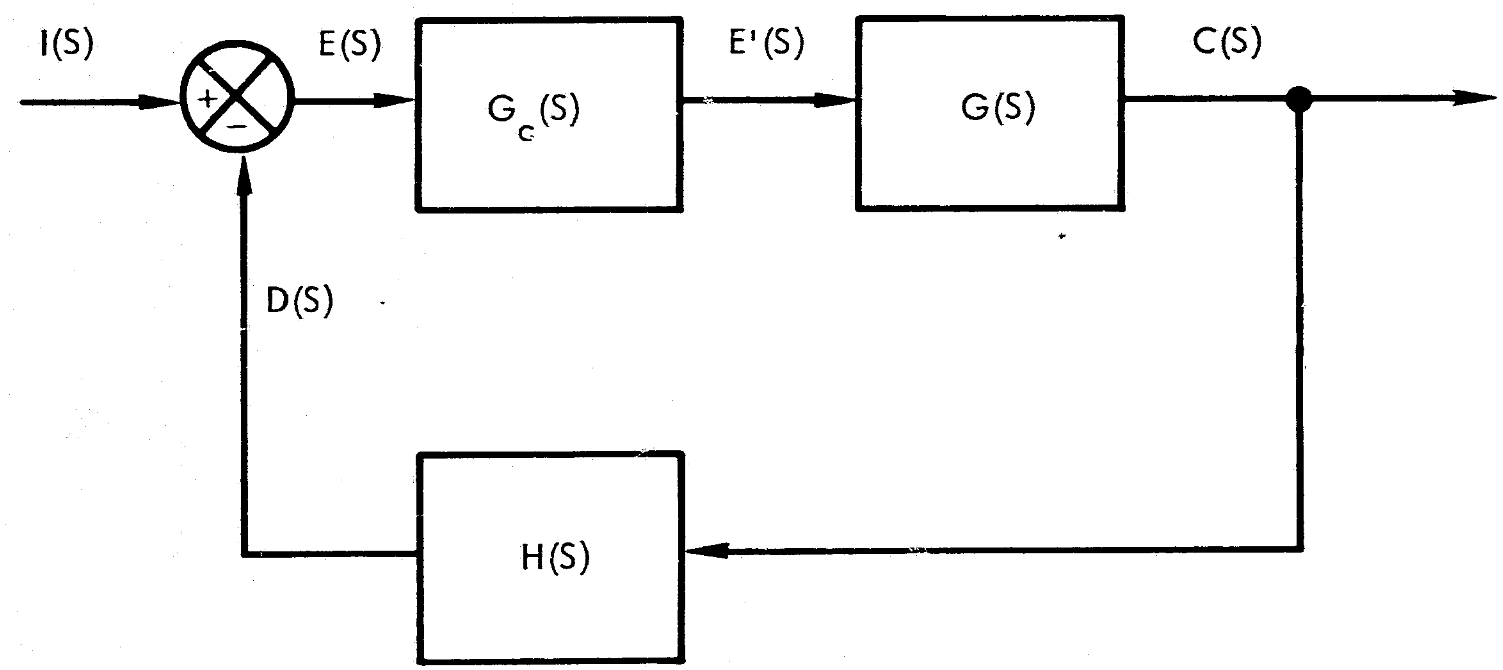


Figure 4. Simplified Functional Block Diagram of Servo System

where:

$E(S)$ = Error signal of servo

$E'(S)$ = Error signal of servo compensation

$I(S)$ = Input signal of servo

$G_{OL}(S) = G_C(S)G(S)H(S)$ = Open loop transfer function of servo

$G_C(S)$ = Compensation network transfer function

$H(S)$ = Feedback transfer function

$G_C(S)G(S)$ = Forward transfer function

The derivation of Equations (1) and (2) are given in Appendix B. The actual equivalent servo model for the CSM HGA is described in Reference 2. The functional block diagram of the CSM HGA Tracking System is shown in Figure 5*, as it is found in Reference 2.

The actual analytical expressions for the response curves found in the measurement procedure can be derived from Figure 5. The derivation will be given in a later report concerning the dynamic study of the CSM HGA servo. The parameters expressions $G_{OL}(S)$ and $G_C(S)$ in Equations (1) and (2), are given below. The parameter values that are substituted into $G_{OL}(S)$ and $G_C(S)$ are found in Reference 2, Table 2-1, under nominal $77^{o}F$.

The open-loop transfer function for the elevation channel is:

$$G_{OL3}(S) = \frac{28.07\left(\frac{S}{6} + 1\right)}{S\left(\frac{S}{66.50} + 1\right)\left(\frac{S}{1.20} + 1\right)\left(\frac{S}{80.00} + 1\right)} \qquad (3)$$

*Figure 5 is inaccurate in several details, it is marked "For Reference Only" and is not intended for general use. A more complete, corrected figure will appear in the dynamic tracking study report.

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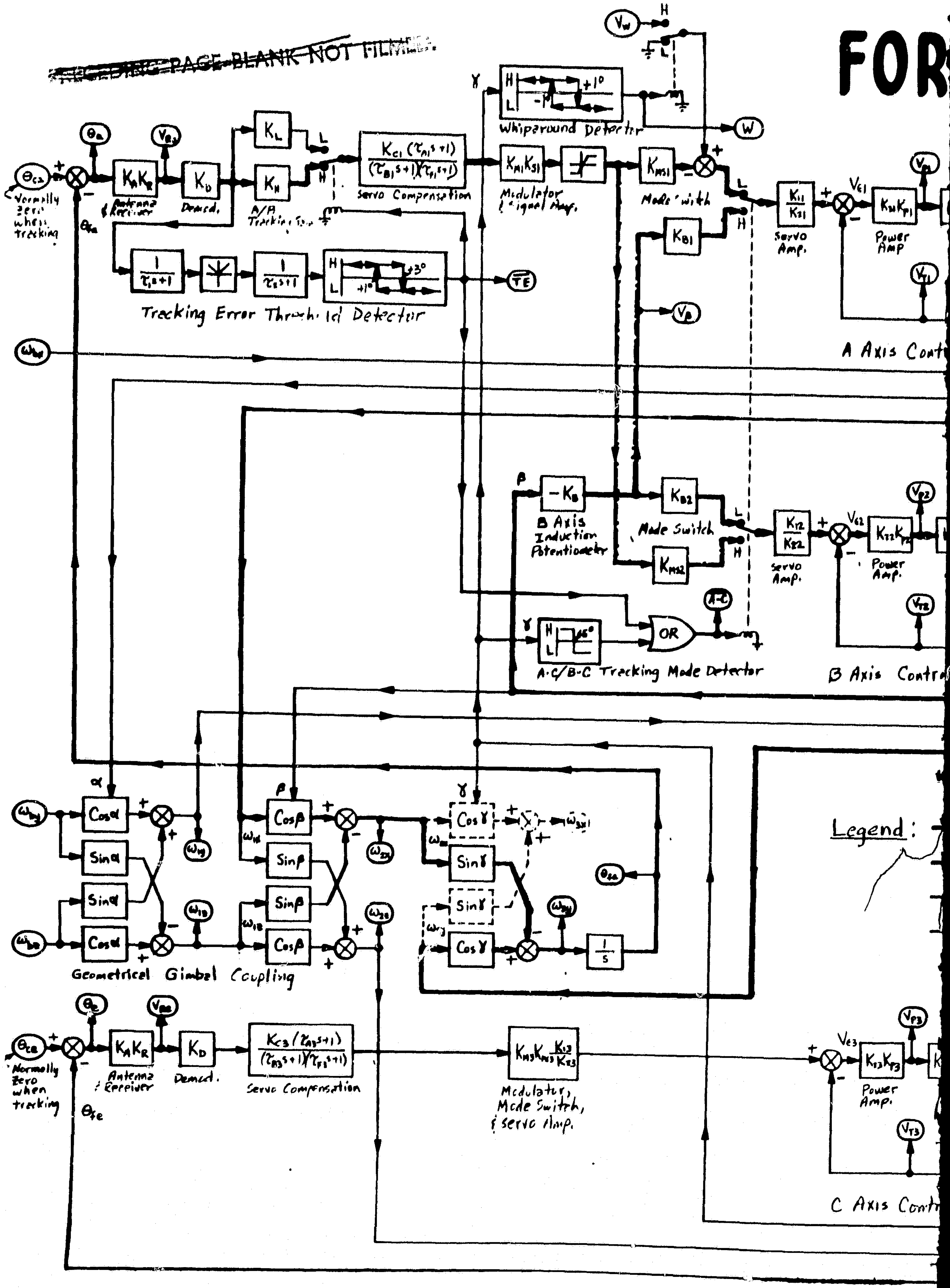

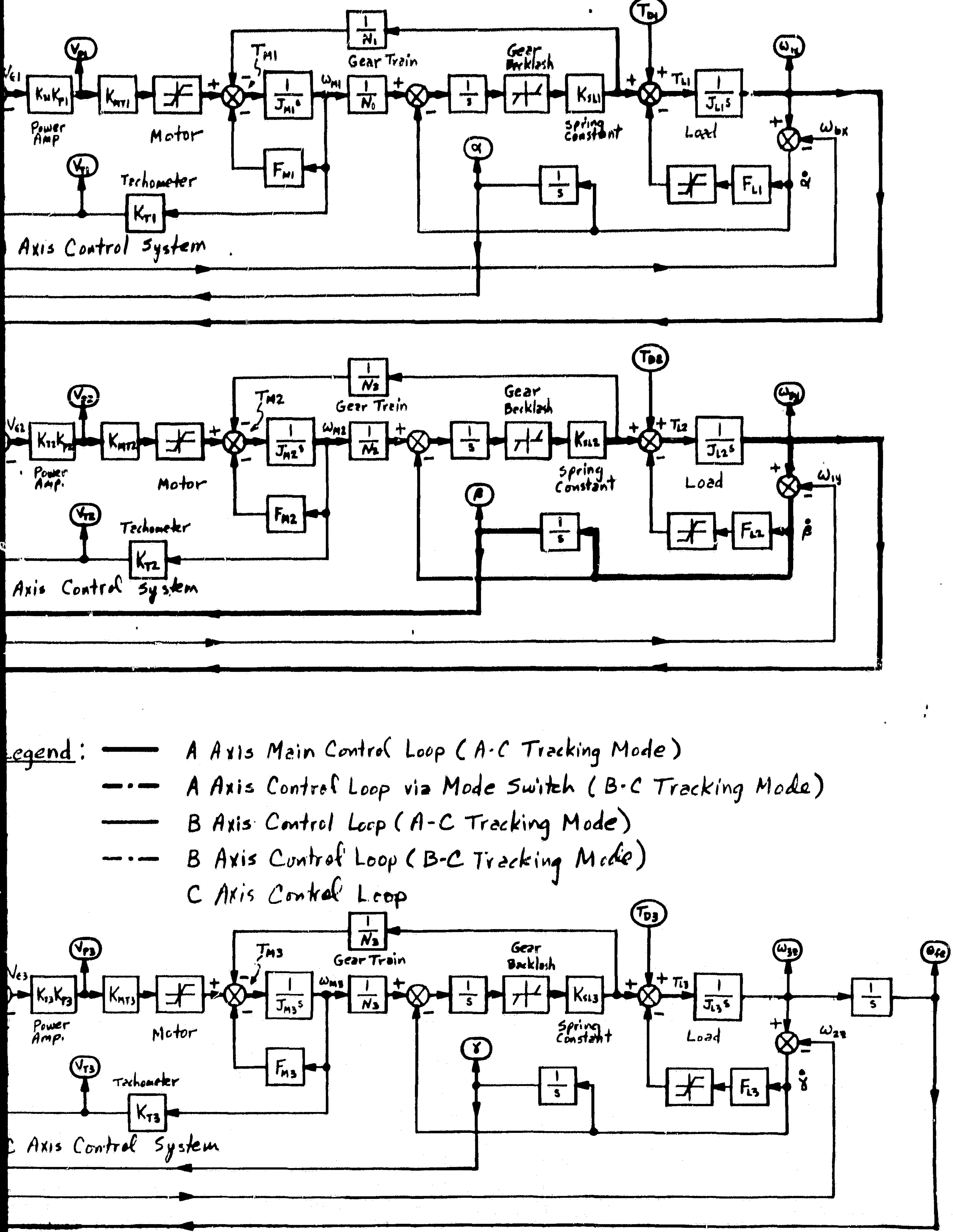

Figure 5. CSM High Gain Antenna Tracking System - Equivalent Functional Block Diagram

and the open-loop transfer functions for the azimuth channel are:

$$G_{OL1(A-C)}(S) = \frac{41.02\left(\frac{S}{4.28}+1\right)\cos\beta\sin\gamma}{S\left(\frac{S}{21.10}+1\right)\left(\frac{S}{66.67}+1\right)} \tag{4}$$

$$G_{OL12(B-C)}(S) = \frac{41.15\left(\frac{S}{4.28}+1\right)\cos\gamma}{S\left(\frac{S}{42.16}+1\right)\left(\frac{S}{0.82}+1\right)\left(\frac{S}{66.67}+1\right)}\left[1+\frac{1.75\cos\beta\tan\gamma}{S\left(\frac{S}{21.10}+1\right)}\right] \tag{5}$$

The subscripts 1, 2, and 3 refer to the A, B, and C axis control system, respectively, and "A-C" corresponds to the A-C tracking mode and "B-C" corresponds to the B-C tracking mode.

The Equation for the azimuth channel is determined by the value of the angle γ and β (see Figure 6). For γ greater than 45°, use Equation (4) and for γ less than 45°, use Equation (5). The curves presented in this report are for $\gamma = 90^\circ$ and $\beta = 0^\circ$ in Equation (4) and for $\gamma = 45^\circ$ and $\beta = 0$ in Equation (5). The transfer function for the azimuth (A/B-axes) compensation network is:

$$G_{C1}(S) = \frac{\left(\frac{S}{4.275}+1\right)}{\left(\frac{S}{0.82}+1\right)\left(\frac{S}{66.7}+1\right)} \tag{6}$$

and the transfer function for the elevation (C-axis) compensation network is:

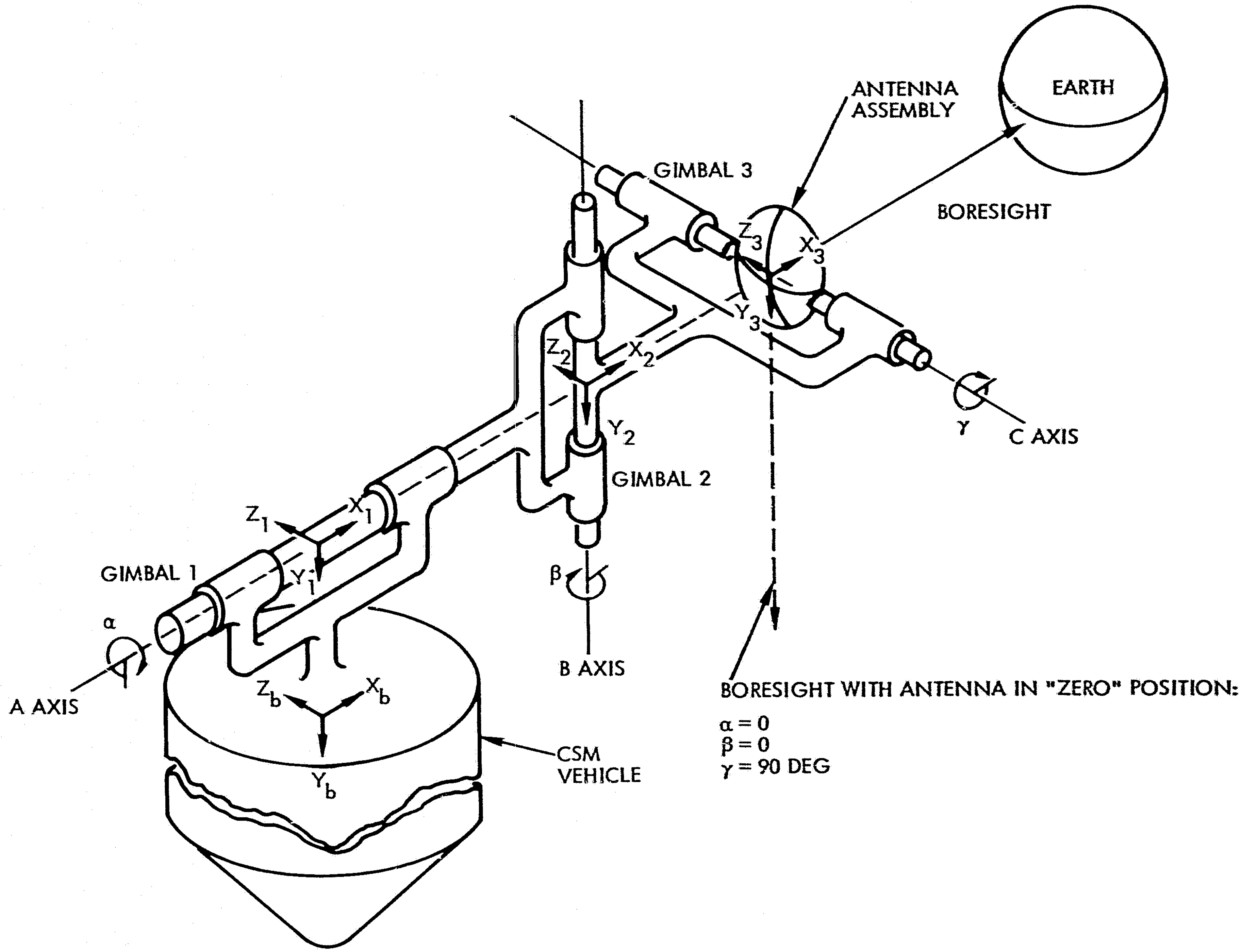

Figure 6. CSM HGA Gimballing System

$$G_{C3}(S) = \frac{\left(\frac{S}{6} + 1\right)}{\left(\frac{S}{1.2} + 1\right)\left(\frac{S}{80} + 1\right)} \qquad (7)$$

The response curves for Equations (1) and (2) are shown in Figures 7, 8, and 9. They are found by substituting Equation (4) into Equation (1) (Figure 7), substituting Equation (5) into Equation (1) (Figure 8), and substituting Equation (3) into Equation (1) (Figure 9). Figures 10 and 11 are the response curves for the azimuth and elevation servo compensation networks which are represented by Equations (6) and (7), respectively. These curves were obtained from TRW's Linear System Dynamic program (HC003C).

4.0 SUMMARY AND CONCLUSIONS

This report has presented a measurement technique for experimentally determining the closed-loop response of the CSM HGA servo system and the transfer function of the elevation and azimuth servo compensation networks. Measured data, obtained through the use of the described techniques, may be used to systematically verify proper operation of the servo system, as well as to verify the CSM HGA servo system analytic model.

In order to implement the test techniques described, an error modulator is required. Such an error modulator may be designed as described in Appendix A, utilizing readily available "off-the-shelf" components. Since this is the only non-standard piece of test equipment used in the test procedure, the methods described for determining the azimuth and elevation transfer function and closed-loop response of the CSM HGA Systems are economically feasible and may be quickly implemented.

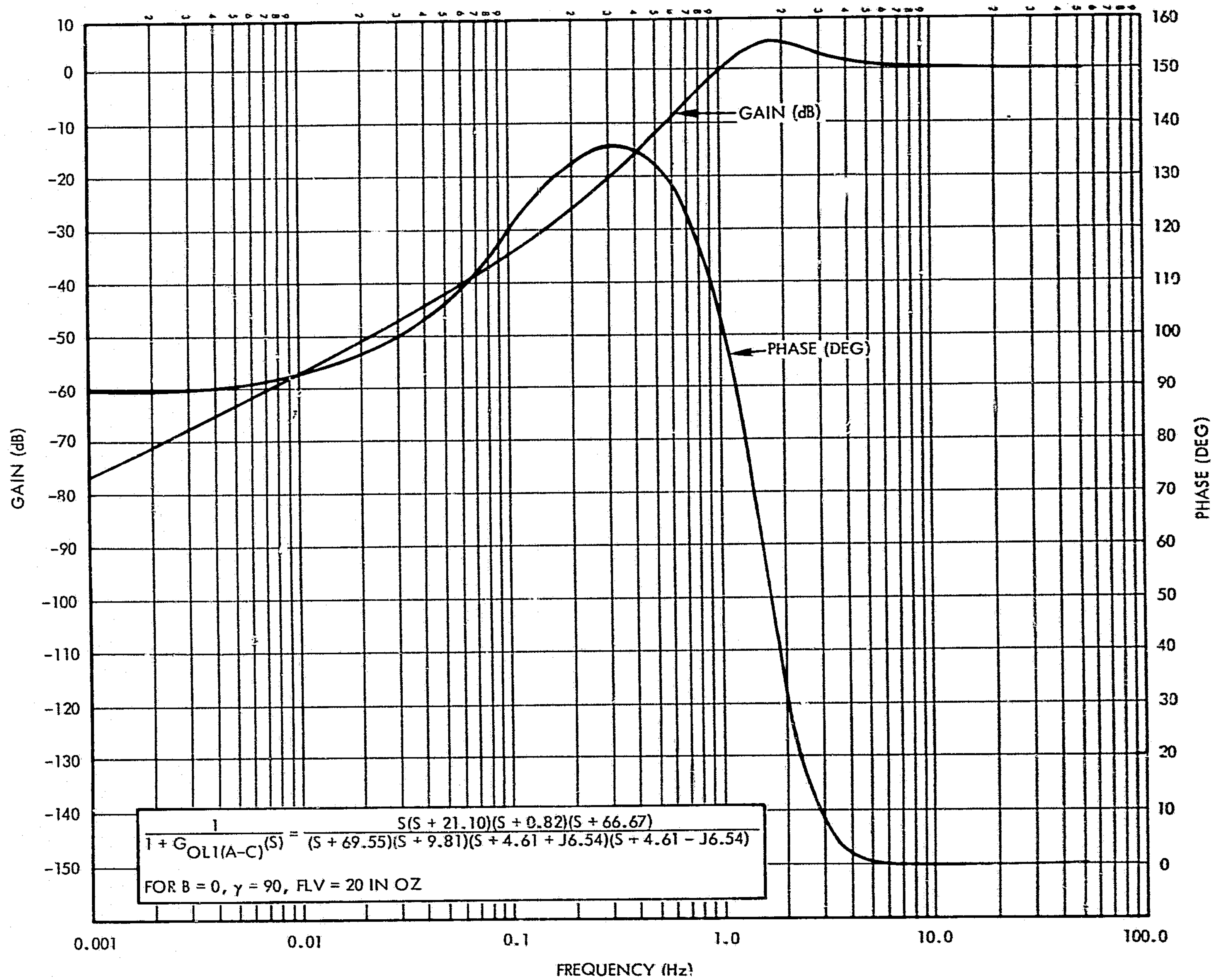

Figure 7. Closed-Loop Response for Azimuth (A-C Tracking Mode) Antenna Tracking Servo (for $\beta = 0^{\circ}$, $\gamma = 90^{\circ}$)

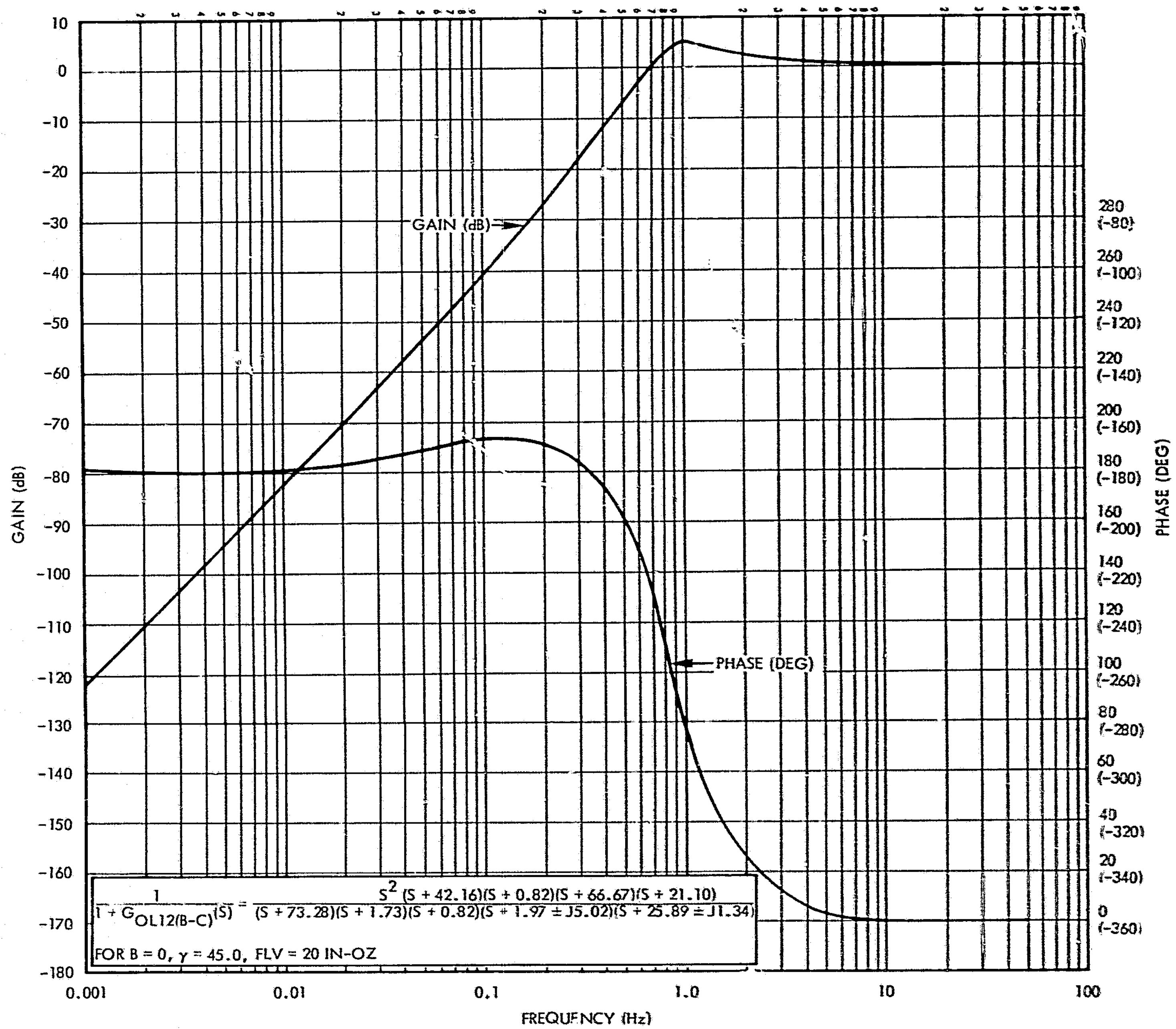

Figure 8. Closed-Loop Response for Azimuth (B-C Tracking Mode) Antenna Tracking Servo (for $\beta = 0^\circ$, $\gamma = 45^\circ$)

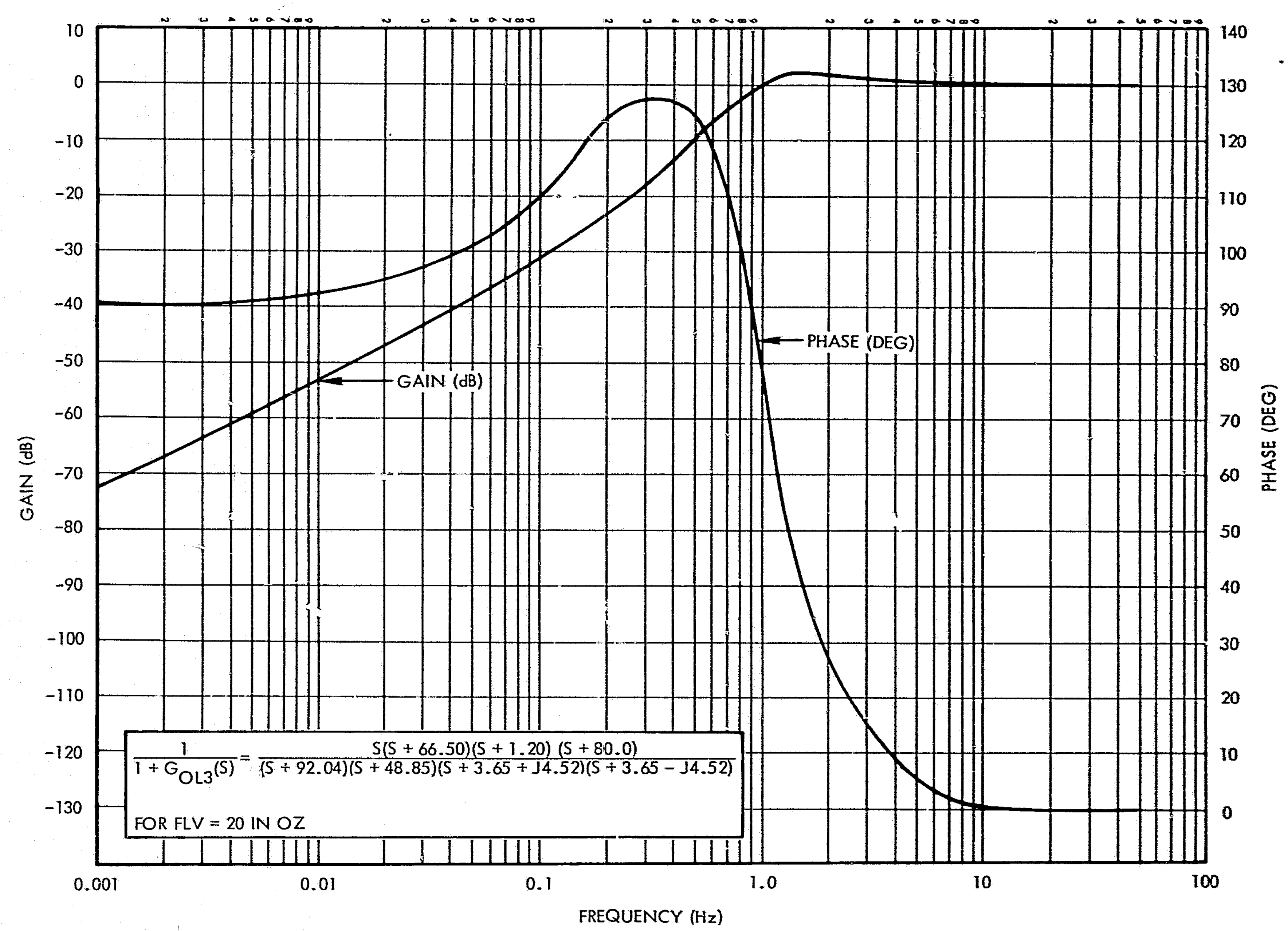

Figure 9. Closed-Loop Response for Elevation Antenna Tracking

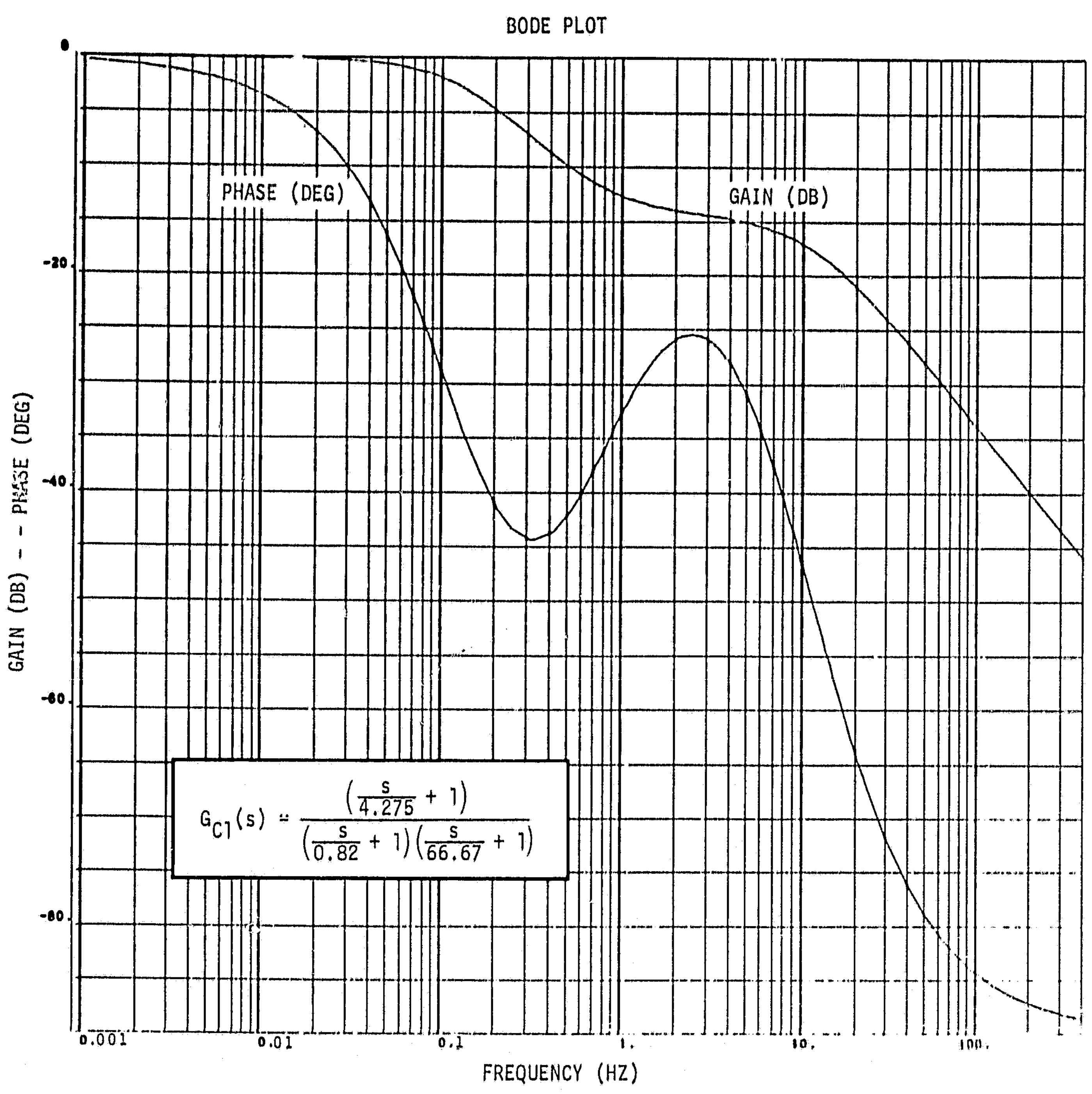

Figure 10. Response Curve of Azimuth Antenna Servo Compensation Network

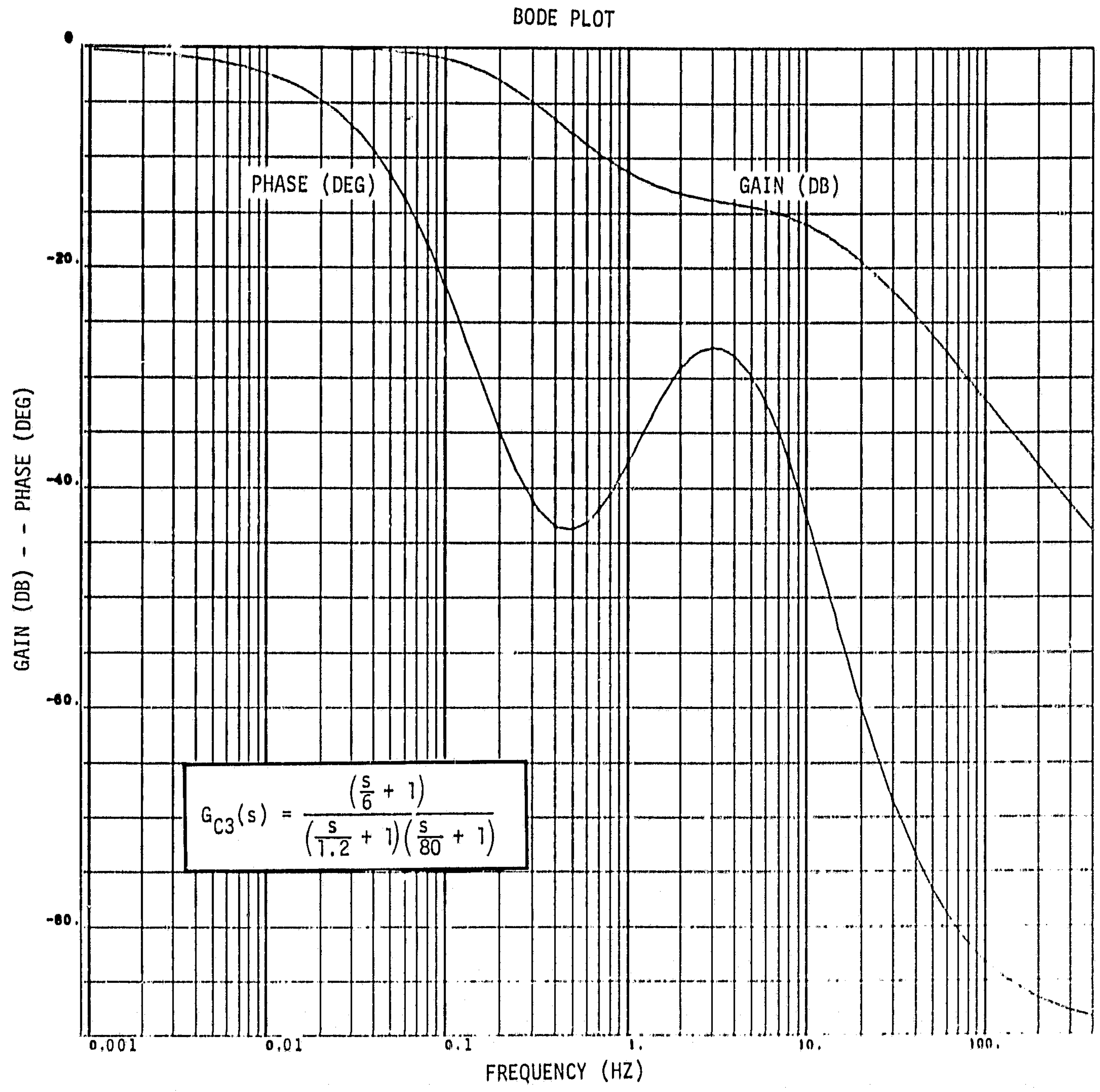

Figure 11. Response Curve of Elevation Antenna Servo Compensation Network

APPENDIX A

DEVELOPMENT OF THE ERROR MODULATOR CIRCUIT

The function of the error modulator used in the test setup in this report is to sample a low frequency sine wave using the available RF antenna track drive references as signals to drive the switches in the error modulator circuit that is given in Figure A-1. The circuit given in Figure A-1 must accomplish the results given in Figure A-2, which shows the input signal, RF drive References, and the desired outputs. To accomplish the desired results , the following operation must take place: For the elevation output,

Time Period	Switch Position
1	Open switch 1 and close switch 2
2	Close switch 1 and switch 2
3	Close switch 1 and open switch 2
4	Close switch 1 and switch 2

and for the azimuth output,

Time Period	Switch Position
1	Close switch 1 and 2
2	Open switch 1 and closed switch 2
3	Close switch 1 and 2
4	Close switch 1 and open switch 2

The signals that drive the switches in Figure A-1 are developed by the logic circuits on Figures A-3 and A-4. The 50 I and 50 II signals (Figure A-3) are formed by inverting and converting the +3v, -50v logic coarse track drive (CTD) and fine track drive (FTD) signals to 0v, 4v logic signals. This is accomplished by the inverting level shifting amplifiers AR3 through AR6. The inverted outputs of AR3 through AR6 are

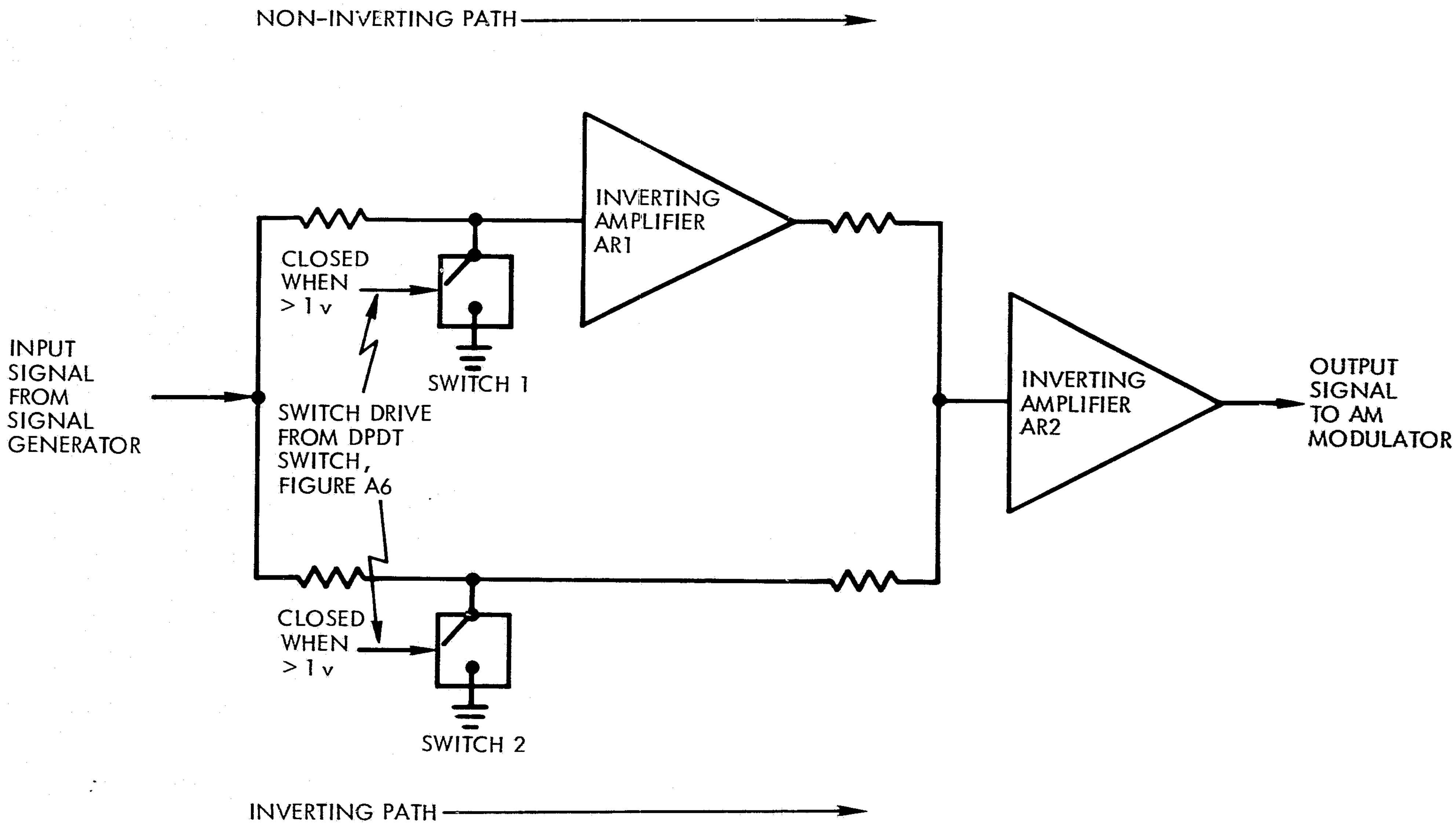

Figure A-1. Functional Diagram of Error Modulator

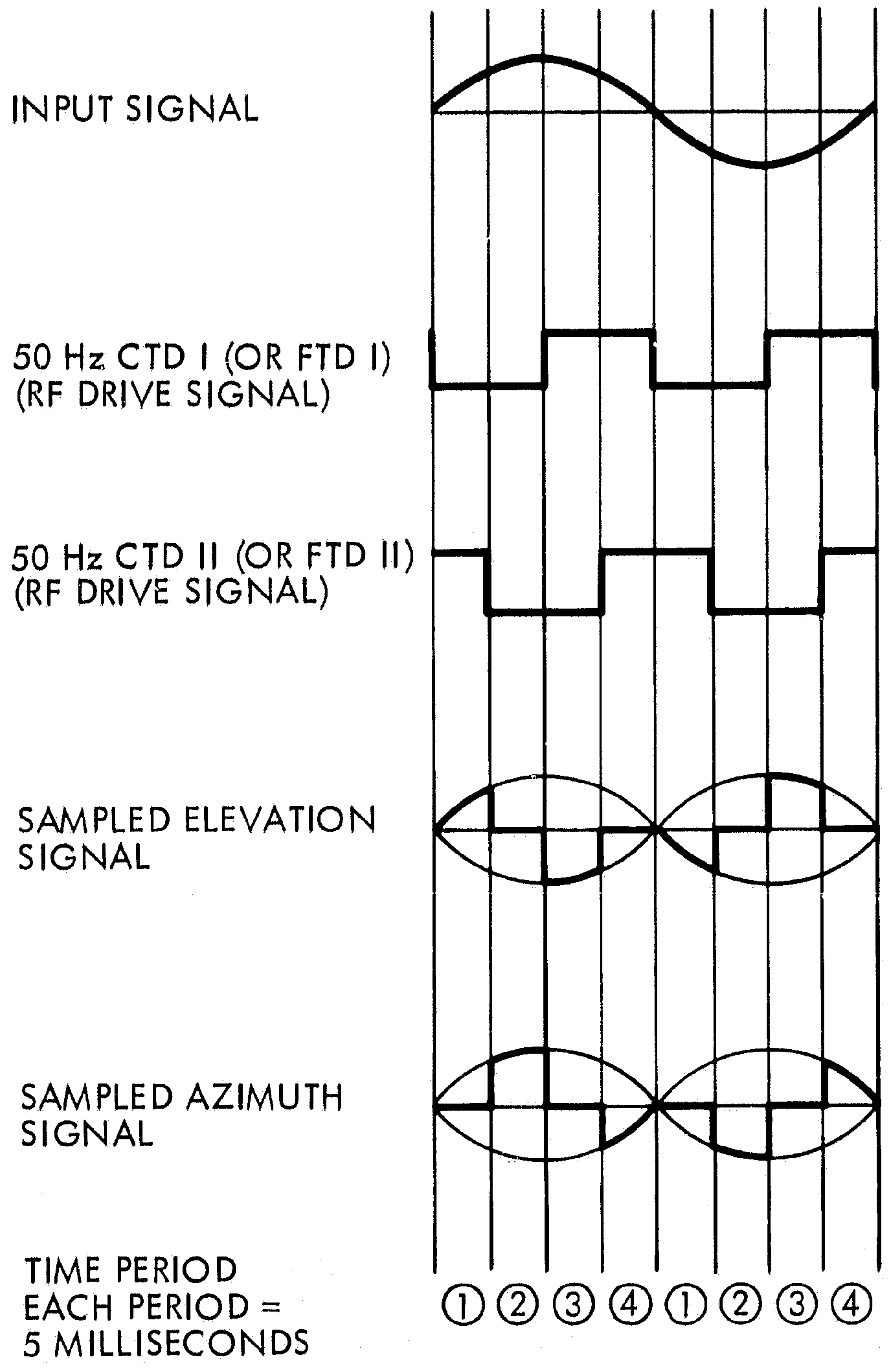

Figure A-2. Input-Output Signals of Error Modulator and RF Track Drive References

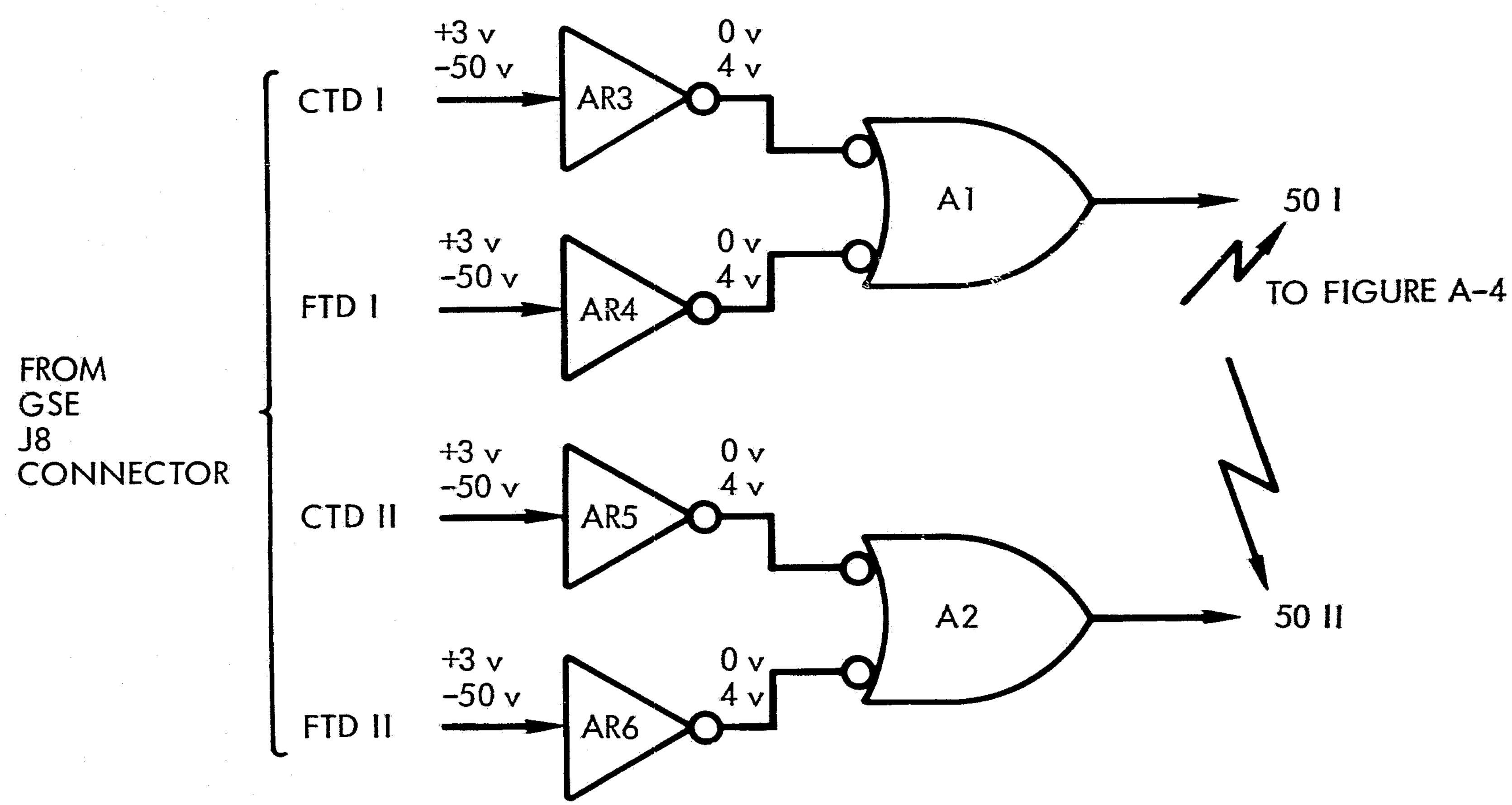

Figure A-3. Generating 50 I and 50 II Signals

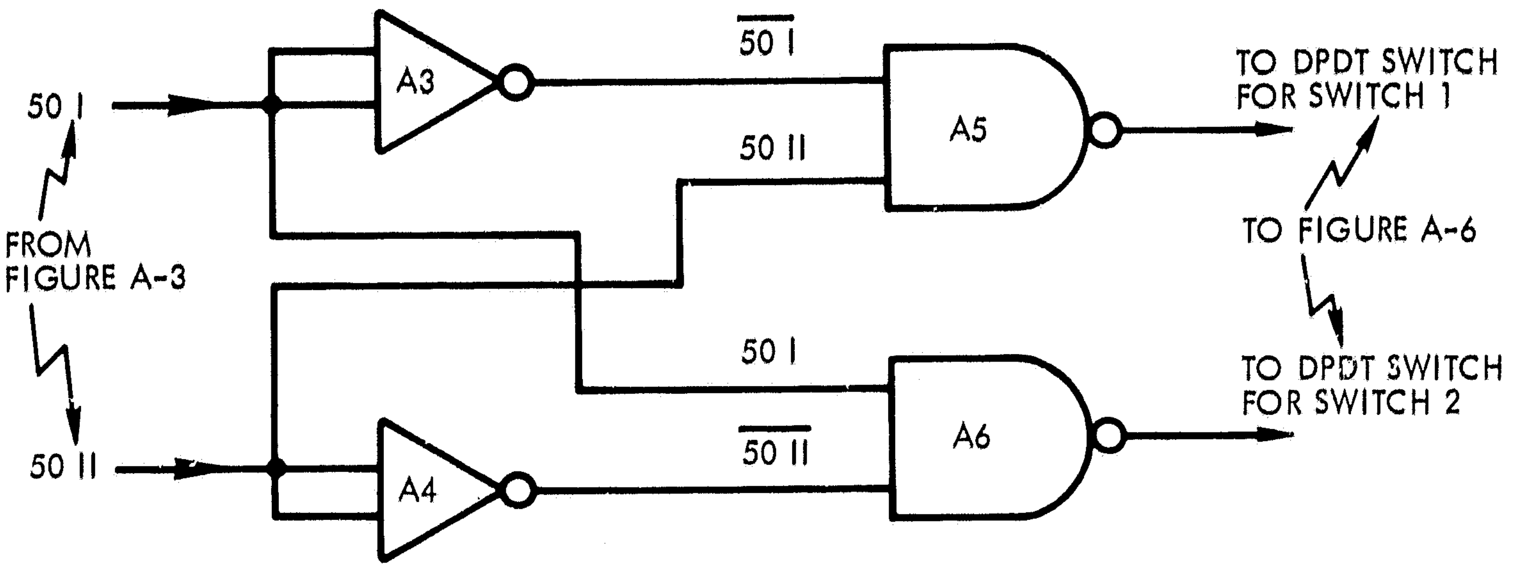

Figure A-4a. Switch Drive for Elevation Signal

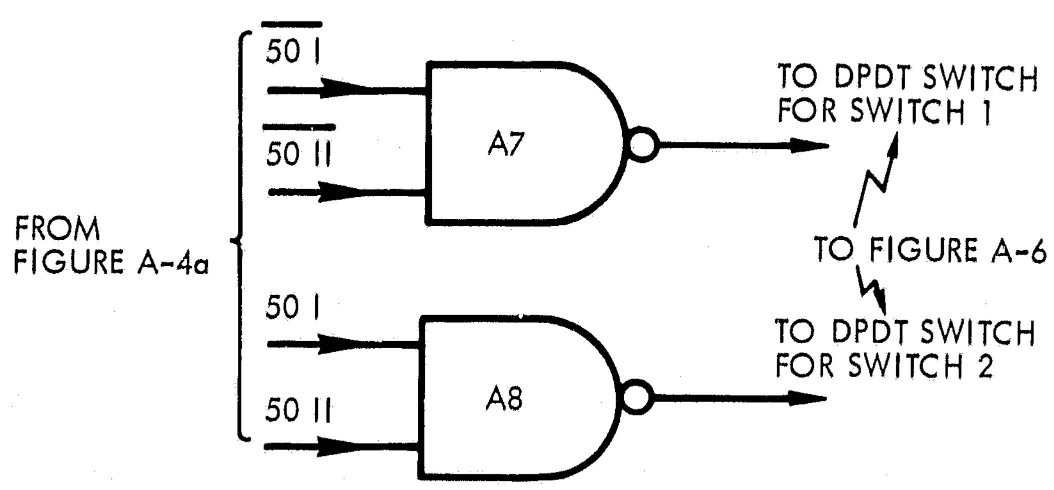

Figure A-4b. Switch Drive for Azimuth Signal

"ORed" by integrated circuit NOR gates A1 and A2, producing the non-inverted 50 I and 50 II signals. Since the CTD and FTD signals are mutually exclusive (i.e., not both on at the same time), 50 I always looks like the 50 Hz CTD I (or FTD I) signals shown in Figure A-2, and 50 II always looks like the 50 Hz CTD II (or FTD II) signal, regardless of whether the system coarse track drive (wide-beam) or Fine Track Drive (narrow beam).

For elevation signals, the circuit in Figure A-4a is used, logic inverters A3 and A4 providing the logically complemented (inverse) signals $\overline{50\ I}$ and $\overline{50\ II}$ (i.e., NOT [50 I] NOT [50 II]). NAND gate A5 "ANDs" $\overline{50\ I}$ and 50 II to form the signal ($\overline{\overline{50\ I} \cdot 50\ II}$), which has the proper form to drive switch 1 of Figure A-1 (see Figure A-5). NAND gate A6 "ANDs" 50 I and $\overline{50\ II}$ to form the ($\overline{50\ I \cdot \overline{50\ II}}$) signal required for the Figure A-1 switch 2.

For azimuth signals, NAND gate A7 (Figure A-4b) "ANDs" $\overline{50\ I}$ and $\overline{50\ II}$ (from Figure A-4a) to form ($\overline{\overline{50\ I} \cdot \overline{50\ II}}$) for switch 1, and NAND gate A8 "ANDs" 50 I and 50 II (also from Figure A-4a) to form ($\overline{50\ I \cdot 50\ II}$) for switch 2. The 50 I and 50 II signals and the outputs of gates A5 through A8 are shown in Figure A-5.

The error modulator is designed to sample either the elevation signal or the azimuth signal, but not both signals at the same time. To accomplish this, a double pole, double throw (DPDT) switch is used. The connection of the DPDT switch is shown in Figure A-6. When this switch is "up", the outputs of gates A5 and A6 are connected to the Figure A-1 switch 1 and switch 2 drive inputs, respectively. When this switch is "down", the outputs of gates A7 and A8 are connected to the switch 1 and switch 2 drives.

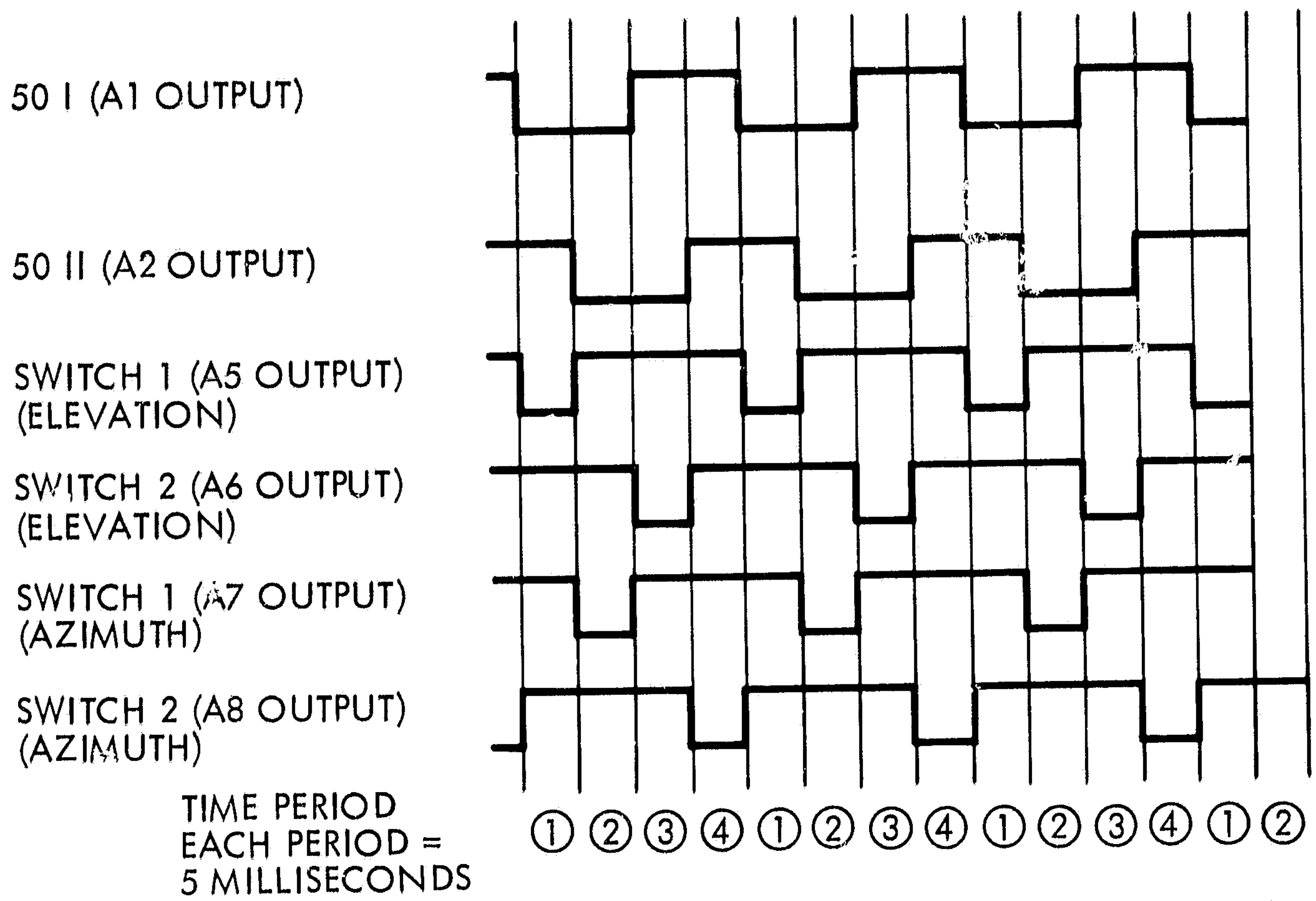

Figure A-5. Signals for Figures A-3 and A-4

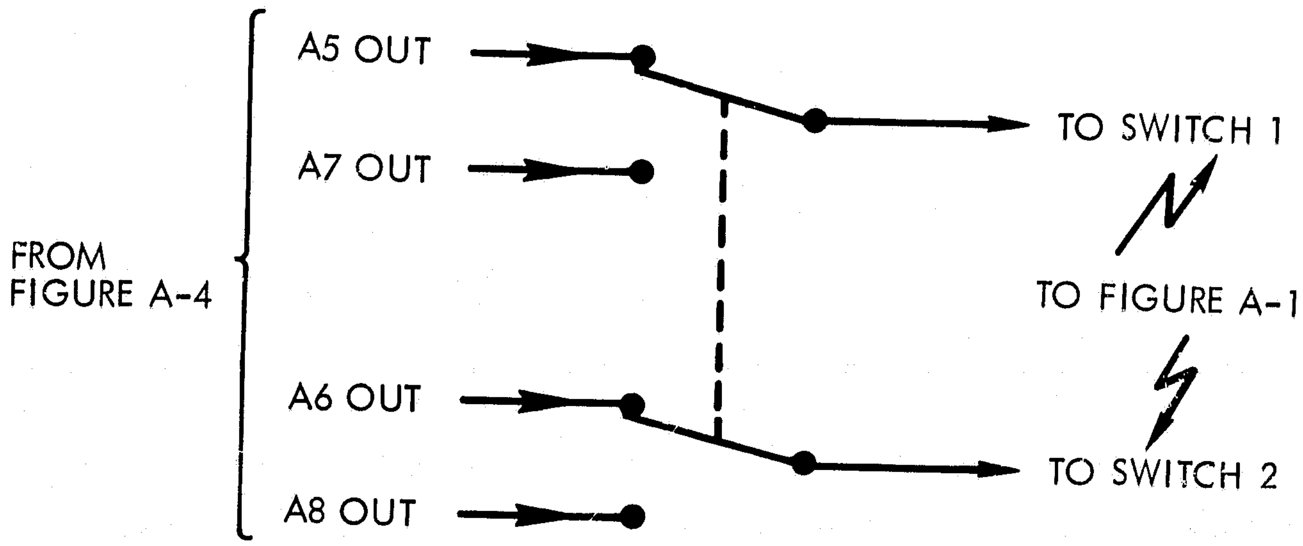

Figure A-6. Double Pole Double Throw (DPDT) Switch. "Up" is Elevation and "Down" is Azimuth.

The parts required to build the error demodulator are available at TRW. They are listed as follows:

4 inverting level shifters (AR3 through 6)

2 SN5400 integrated circuit logic elements - TI

6 2N3904 transistors - Motorola

3 IN3600 and 1 IN3062 silicon diodes

2 DEC A200 operational amplifiers

1 DPDT switch

APPENDIX B

DERIVATION OF THE ERROR RATIO

The error ratio of the simplified servo system (given in Figure B-1 for convenience) is found in the following way:

(1) From Figure B-1 the following expressions are written:

$$E(S) = I(S) - D(S) \tag{B.1}$$

$$E'(S) = G_C(S)E(S) \tag{B.2}$$

$$C(S) = G_C(S)G(S)E(S) \tag{B.3}$$

$$D(S) = C(S)H(S) \tag{B.4}$$

(2) Substitute (B.3) into (B.4), (B.4) into (B.1) and solve for the error ratio $\frac{E(S)}{I(S)}$.

$$E(S) = I(S) - G_C(S)G(S)H(S)E(S)$$

$$I(S) = E(S)\,[1 + G_C(S)G(S)H(S)]$$

$$\frac{E(S)}{I(S)} = \frac{1}{1 + G_C(S)G(S)H(S)} \tag{B.5}$$

define

$$G_{OL}(S) = G_C(S)G(S)H(S) = \text{Open Loop transfer function}$$

then

$$\frac{E(S)}{I(S)} = \frac{1}{1 + G_{OL}(S)} \tag{B.6}$$

A modified error ratio may be found by substituting (B.2) into (B.6) and solving for the ratio $\frac{E'(S)}{I(S)}$.

$$\frac{E'(S)}{I(S)G_C(S)} = \frac{1}{1 + G_{OL}(S)}$$

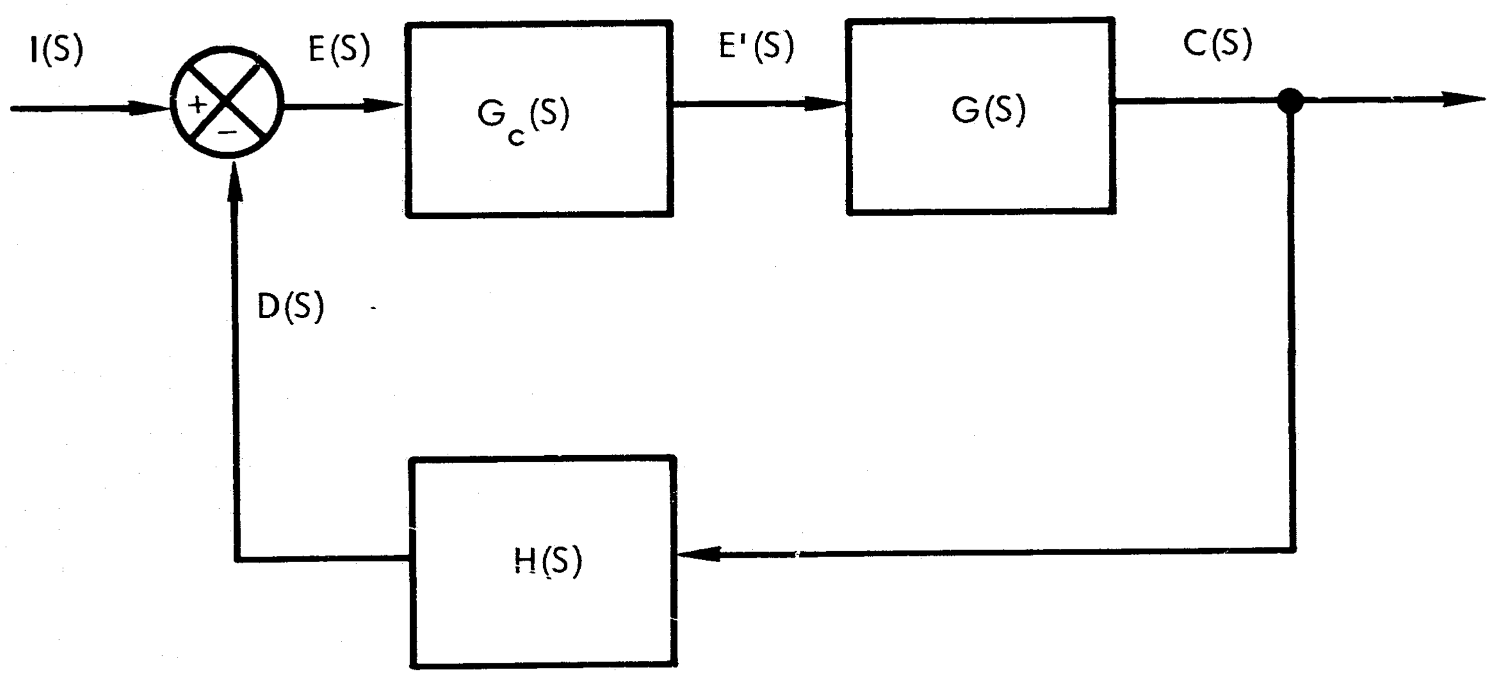

Figure B-1. Simplified Functional Block Diagram of Servo System or

$$\frac{E'(S)}{I(S)} = \frac{G_C(S)}{1 + G_{OL}(S)} \tag{B.7}$$

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